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Directed-energy Models for Distributed, Synthetic Environments

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Abstract

Directed Energy (DE) weapons and weapons effects are not accurately modeled in a distributed simulation environment. The Distributed Interactive Simulation (DIS), and High Level Architecture protocols were created when DE weapons were conceptual or in the initial development stages. IEEE 1278.1a is currently being updated by the Simulation Interoperability Standards Organization (SISO) DIS Product Development Group (PDG). The DE Tiger team, part of the DIS PDG, designed two new DIS PDUs for high fidelity DE distributed simulation: DE Fire and DE Damage Status. This paper presents the DE weapon modeling techniques for precision and area DE weapons as well as Gaussian beam spot modeling algorithms. This paper also presents the ACE experiment plans and results.

Keywords

DIS, distributed simulation, simulation modeling

1. Introduction

The Directed-Energy (DE) Tiger team, which was part of the Simulation Interoperability Standards Organization (SISO) Distributed Interactive Simulation (DIS) Product Development Group (PDG), has developed methods to model DE weapons and their effects on targets. This high-fidelity DE model was accomplished by creating two new DIS Protocol Data Units (PDUs): DE fire and DE damage status. In November of 2006, September 2007, August 2008, and May 2009, experiments were conducted to test the initial design, PDU exchange algorithms, fidelity and interoperability with legacy simulations, and recommend changes if required. This was a unique opportunity to test DE model design before incorporation into the Institute of Electrical and Electronic Engineers (IEEE) 1278.1a-201x Model deficiencies were discovered, and suggested changes were tested to verify the corrections were valid. These changes have been submitted to the DIS PDG. In addition to the corrections submitted, additional modeling capabilities for DE weapons and their effects were also added. This paper describes the DE high-fidelity models, experiment plan and results, and improvements to DE distributed, synthetic models.

2. Directed-energy High-fidelity Models For Synthetic Environments

Developing distributed DE weapons and weapons-effects models presented several challenges. First, many DE models were ‘stand alone’, and did not interact with any other DE model. Many DE models have second- and third-order weapons-effects models that perform many calculations. Such calculations cannot be conducted in a real-time distributed environment. So, the question is: ‘What kind of and how much information transfer is required for adequate DE modeling?’ The answer should provide adequate information so that current stand-alone DE models can implement their existing algorithms and provide accurate weapons and damage calculations in a distributed, synthetic environment.

Second, there are two ways to model DE weapons in a distributed environment: (1) use a pure stochastic model where initial conditions and events are entered into a table and then the probable effect is produced; (2) use an algorithmic model where a DE model continuously provides a power model of the energy transferred to the target. The target then implements a lethality algorithm and determines the associated damage. The second option was chosen as the best modeling approach because it meets the DIS standard paradigm requirements.[1]

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14. ABSTRACT

Directed Energy (DE) weapons and weapons effects are not accurately modeled in a distributed simulation environment. The Distributed Interactive Simulation (DIS), and High Level Architecture protocols were created when DE weapons were conceptual or in the initial development stages. IEEE 1278.1a is currently being updated by the Simulation Interoperability Standards Organization (SISO) DIS Product Development Group (PDG). The DE Tiger team, part of the DIS PDG, designed two new DIS PDUs for high fidelity DE distributed simulation: DE Fire and DE Damage Status. This paper presents the DE weapon modeling techniques for precision and area DE weapons as well as Gaussian beam spot modeling algorithms. This paper also presents the ACE experiment plans and results.

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The goal was to establish DE models in the engagement domain. Simply put, all DE engagements would be modeled as a shooter that transfers power to a target, and then the target determines if energy transfer occurred, and if it occurred, the effects from this energy transfer. By separating the DE weapon model from the target model, two DE modeling requirements are defined: (1) every shooter and target simulation shall model its component of the process; (2) the interface between simulations shall remain constant. This approach requires each simulation to provide a concept of each model, both shooter and target, for other systems that wish to model DE in a simplified form and maintain the established interface. The next step was to define the information transfer parameters for the current DE weapons models and target-effects models.

2.1. Directed-energy Weapons Models

Directed-energy weapons are divided into the following four system types.

1. High Energy Lasers (HEL), such as the Airborne Laser, the Advanced Tactical Laser, or the Mobile Tactical High Energy Laser (MTHEL)
2. Low Energy Laser (LEL), such as the Personnel Halting and Stimulation Response (PHASR) rifle, the Laser Dazzler, the Saber Shot Laser Dazzler, or the Dissuader Dazzler
3. High Powered Microwave (HPM), such as Active Denial System (ADS)
4. Directional Acoustic, such as the Long Range Acoustic Device (LRAD).

Each has different weapons characteristics and differs in the type and amount of damage they cause on targets. In addition, all DE weapons are modeled as being attached to an entity. As such, two categories were defined for DE weapons. They are DE precision and DE area weapons. The DE fire PDU models both categories using similar algorithms because each is modeled as transferring energy from the shooter to the target.

Next, the information required for the target to initiate a damage calculation was defined as the following:

1. Shot Start/Stop Time (seconds)
2. Cumulative Duration (seconds)
3. Aperture/Emitter Location in Firing Entity Coordinates (X, Y, Z)
4. Aperture Diameter (meters)
5. Wavelength (meters)
6. Peak Irradiance (watts/meter^2)
7. Pulse Repetition Frequency (hertz)
8. Pulse Width (seconds)
9. Pulse Shape (Enumerated),
10. Aim Point (Precision or Area)

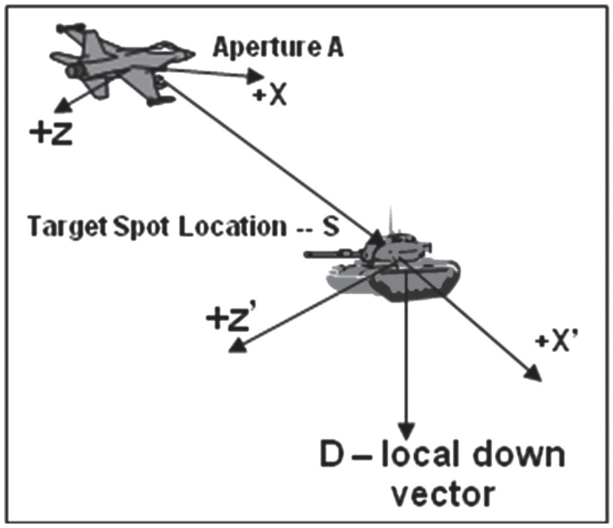

Figure 1. Coordinate transfer

These parameters were deemed necessary for high-fidelity directed-energy modeling.

Next, coordinate-transformation algorithms were required because the shooter and target are typically in different coordinate frames of reference; thus, coordinate transformation is required for accurate energy-transfer calculations and effects modeling. Figure 1 shows an example of the shooter and target frames of reference.

The coordinate-system transfer relationships are a series of vector cross products. For the X to X' vector, the transformation is:

$$X' = \frac{S - A}{|S - A|} \tag{1}$$

where S is the target spot location and A is the aperture location. For the Y to Y' vector transformation, there are two specific cases. The first is if the beam is not parallel to the local down vector, and the second is if the beam is parallel to the local down vector. The two transformations are:

$$Y' = \frac{D' \times X'}{|D|} \text{ if } \frac{D' \times X'}{|D|} \neq \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \tag{2}$$

Otherwise:

$$Y' = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{3}$$

For the Z to Z' transformation, one can use the solutions already obtained from equations 1, 2, and 3 to get:

$$Z' = X' \times Y' \tag{4}$$

The energy transfer can now be modeled in a distributed environment using the previously described coordinate-transfer relationships. The beam-spot model is described below.

2.2. Directed-energy Beam-spot Model

The typical DE precision weapon usually includes active beam-control systems that are designed to concentrate the transferred energy onto a particular spot on the target. The DE spot profile on the target can have many shapes due to several variables. These variables include DE weapon characteristics (frequency, initial beam profile, aperture size, platform jitter), atmospheric effects; the instantaneous velocity and acceleration of both the shooter and the target; the distance of the shooter from the target; and the 'jitter' of the DE weapon once it reaches the target.

The beam spot at the target is characterized by the beam-spot size and irradiance profile shape in the plane normal to the beam path. Typically, the irradiance profile is a Gaussian shape whose peak is given by the peak irradiance field described above. Its width is characterized by the distance from the center at which the irradiance level is $1/e^2$ times the peak irradiance. This distance is defined as $\sqrt{2}\sigma$, where σ is the standard deviation of the Gaussian function.

Spot shapes can range from a perfect circle to a crescent shape to an ellipse. A circular shape can result from a beam with no spreading phenomena. A crescent shape can result from several different spreading phenomena, such as different atmospheric pressures; the transverse direction of either the shooter or target; and the spot duration. An elliptical shape could result from beam-spreading phenomena driven by a change in the aspect angle between the weapon and the target, or by beam dithering in one direction. The aspect angle induced spread is oriented in the direction of the transverse velocity, but the dither spread might be in another direction. The resultant elliptical shape will have some orientation with a major and minor axis width, thus two sizes must be specified as the beam-spot cross-section semi-major size and beam-spot cross-section semi-minor size.

For distributed-modeling purposes, an elliptical beam-spot size model was chosen as the best model that would represent all possible shapes, and could be used for first-order real-time lethality damage model calculations. The orientation of the ellipse is specified by the beam-spot cross-section orientation angle field. The beam coordinate system is a right-handed Cartesian coordinate system with the center of the beam along the *x*-axis of the system. The beam coordinate system is constructed as:

- The *x*-axis is the vector from the firing entity aperture to the target spot.
- The *y*-axis is the local 'down' vector at the target spot crossed into the *x*-axis.
- The *z*-axis is the *x*-axis crossed into the *y*-axis.

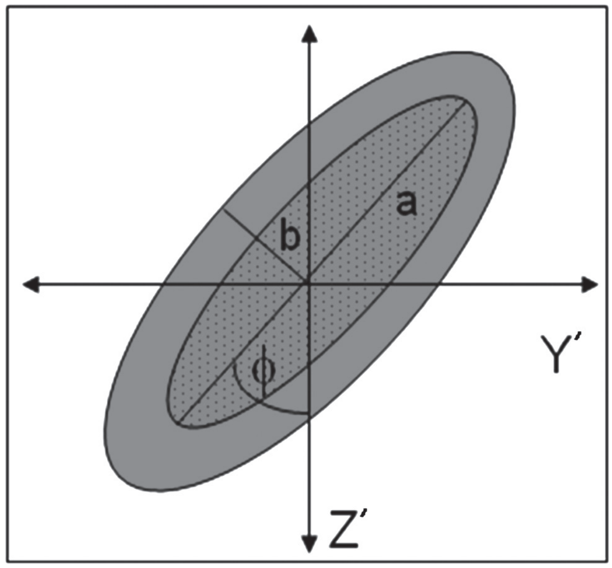

Figure 2. Beam-spot model

The irradiance at a point on the *y'z'* plane is then given by:

$$I(y, z) = I_{Peak} e^{-\left(\frac{y_c^2}{r_y^2}+\frac{z_c^2}{r_z^2}\right)} \quad (5)$$

where:

$$z_c = z\cos(-\varphi) - y\sin(-\varphi)$$

$$y_c = z\sin(-\varphi) + y\cos(-\varphi) \quad (6, 7)$$

Note that *y*, *z* is the point of interest in the *y*–*z* plane, which is the plane normal to the line-of-sight of the beam coordinate frame. Parameters r_y and r_z are the azimuth beamwidth and elevation beamwidth, respectively. The beam-spot model[2] is shown in Figure 2.

2.3. Directed-energy Weapons Tracking in a Distributed Environment

Modeling an active tracking system for a DE weapon poses a challenge in the distributed simulation environment. In the real world, a DE shot emerges from the aperture of a weapon – a well-known location – and arrives at the target spot almost instantaneously. One way to model the current state of a shot would be a simple line segment in a DE fire PDU record. But typical DIS network latencies[3] combined with a fast maneuvering target or terrain database differences between simulations make it unreasonable to model the origin and destination of a laser using DIS world coordinate records. These would most likely result in the shooter, the target, and other observers 'seeing' completely different resulting shots. A higher-fidelity model that is insensitive to

these degrading effects is required to characterize beam-spot tracking. The DE fire PDU record addresses this by identifying the target entity and then providing beam-spot location, velocity, and acceleration information relative to the origin of that entity. This allows dead reckoning of the target spot motion based on each simulation's notion of the current target-entity state, thus canceling these accuracy-degrading effects. Note, however, that problems may arise if the firing and target simulations use different geometric models for the target. One way to resolve this was to incorporate common geometric models in the entity damage status PDU parameters, which are described later.

2.4. Directed-energy Area Aim Point Record

DE area weapon modeling is accomplished by using the area aim point records in the DE fire PDU. The energy deposited in a given area is modeled as affecting one or many targets in that area. Separate weapons effects can be modeled for each target by the beam-antenna parameter record and the target energy deposition record. The beam-antenna record specifies the direction, pattern, and polarization of the DE area weapon, which has been described in detail.[4] The target energy deposition record contains the target ID and the peak irradiance in watts per square meter.

2.5. Directed-energy Damage-effects Models

In DIS version 6, the damage caused by conventional weapons is modeled in the entity state PDU. However, DE weapons-damage models required additional parameters, so the entity damage status PDU was created. The entity damage status PDU models structural damage and temperature effects, complementing the entity state PDU appearance bits. Issuance rules are also defined for the DE fire, damage status, and legacy fire and detonate PDUs. The DE fire PDU, entity damage status PDU structures and associated enumerations are given at the end of this article. Low- and high-fidelity exchange diagrams have been published.[2]

2.6 Mixed-Fidelity Considerations

For distributed events, there will be a mixture of non-DE simulations with higher-fidelity DE simulations. It was decided that the high-fidelity DE simulations are required to send information that the non-DE simulations can process. A mixed-fidelity algorithm was developed[2] that involved the issuance of DE fire PDUs with conventional fire PDUs, and the issuance of a detonate PDU after the last DE fire PDU has been sent. The non-DE simulations would obtain shooter and target information from the fire, detonate, and entity state PDUs. The algorithm ensures that all simulations would be aware of and have the information necessary to process a DE engagement, which is described next.

2.7. Directed-energy PDU Mixed-fidelity Engagement Model

A high-fidelity DE engagement is modeled by the following algorithm. First, a DE simulation sends a DE fire PDU indicating weapon on or fired. This is immediately followed by a fire PDU. Then, additional DE fire PDUs may be sent depending on weapon and engagement type. The engagement then terminates with a final DE fire PDU, followed immediately by a detonation PDU. A simulation that transmits the DE fire PDU is also required to transmit the legacy fire and detonation PDUs. Pulsed DE weapons, where the laser may appear to pulse as a result of several different physical effects or phenomena, are modeled as a continuation of a single engagement, and no additional fire or detonation PDUs are issued. The DE fire PDU may be sent multiple times while a shot is in progress to allow the receiving simulation to continuously assess damage, and provide immediate feedback by transmitting entity state and entity damage status PDUs. The target is also required to dead reckon the weapon impact point.

2.8. Future Directed-energy Model Considerations

There are two DE effects not modeled at this time: (1) if a DE precision weapon misses the target; and (2) reflection modeling for collateral damage. Item 1 presented some challenges on how to accurately model a missed shot. First, the shooter would have to determine how far the beam travels, and when the beam has reduced lethality such that no damage would occur to a target. Conventional algorithms for missiles are that if a missile misses the target that is 'owned' by a constructive simulation that is generating many targets, it will calculate the path of the missile, and then determine if any of its targets are in the path of the missile. Such algorithms are complex and would require many calculations. For DE precision weapons, this could be applied, but path calculations would be required quickly because of the extremely small latency of the beam.

Modeling for collateral damage from precision DE weapons was not considered due to the highly complex second- and third-order calculations. There are many variables involved, such as beam scatter with respect to other targets in the area, the amount of energy reflected, and the direction of the energy reflected. In addition, coordinate-system transformations for each reflection would be required to accurately calculate the energy transfer. These, plus other DE weapons effects will be addressed in future discussions and experiments.

Another future effort is to model DE in the High Level Architecture (HLA) protocol. The HLA model was not part of the DE Tiger team effort. However, DIS models can be converted to HLA models. Efforts are underway to design an HLA Base Object Model (BOM). The shooter and target

models would be included in the BOM. The DE HLA BOM design will be presented in subsequent papers.

2.9. Directed-energy Weather-effects Models

Weather effects were not modeled in this effort. Weather-effects models are still somewhat new in a distributed environment. However, weather-effects models can be added in the DE fire and damage status PDU variable records, if required.

3. Directed-energy PDU Experiment

Once the DE models for distributed simulation were developed, they were submitted to the SISO DIS PDG for inclusion into the new IEEE 1278.1a-200X, DIS Protocol standard. In addition, a DE PDU experiment was proposed to the Air Force Research Laboratory (AFRL), Kirtland Air Force Base, New Mexico. The Advanced Concepts Event (ACE) 06, in October 2006, was the perfect venue to test the newly developed DE distributed models. The experiment proposal was accepted and funded by AFRL for execution in ACE 06, ACE 07, and ACE 09. DE PDU experiments were conducted during each ACE.

The DE experiment was a unique opportunity that could test proposed high-fidelity weapons modeling before incorporation into a distributed simulation standard. The experiment had three phases: software development and unit test; integration test, and the execution of specific DE PDU experiments. Each phase provided valuable feedback for standards development and design. Additional details can be found in the Directed Energy Experiment Test Plan and Results for the Advanced Concept Event 06,[5] and Directed Energy Experiment Test Plan and Results for the Advanced Concept Event 07.[6]

3.1. Directed-energy Goals and Experiment Parameters

The DE experiment goals were: (1) test the proposed DE PDU structures, issuance rules, and modeling algorithms; (2) fidelity/interoperability testing of higher-fidelity DE simulations and legacy simulations; and (3) recommend changes to the structure if deficiencies are found.
The DE experimental parameters were:

1. Conduct experiments on a non-interference basis with ACE 06 and ACE 07.
2. Rely on unclassified damage tables provided by AFRL.
3. Only test HEL weapons simulations.
4. Only PDU structures and data exchange were tested.
5. Real-world DE weapons performance was not modeled or tested.
6. The HEL weapon duration was automatically set by the HEL simulation.

3.2. Directed-energy Experiment Resources

The DE resources used were the Distributed Missions Operations Center (DMOC) F-16 HEL Fighter, the Scenario Toolkit And Generation Environment (STAGE) simulations, and the Distributed Interactive Simulation Network Analysis Tool (DISNAT) data logger. These systems were modified to send, receive, process, and record the DE PDUs. Other resources used but not modified were the DMOC DIS Filter and the Joint Conflict and Tactical Simulation (JCATS).

3.3. Software Development

Software development requirements were derived from Problem Change Request (PCR) 152[2] for the DMOC STAGE and F-16 HEL simulations. The software requirements were the creation of two new DIS PDU structures, modifying existing algorithms for PDU transmission, and adding the new DE PDU structures to the DMOC DISNAT data recorder for recording and analysis. Each system was unit code tested to verify that the correct PDU structures were created according to PCR 152.[2] In addition, all required enumerations were reviewed and verified.

During software development, three issues were discovered. First, the new 1278.1a-200X DIS PDU header adds a PDU status field. This field was added after DE Tiger team approval to provide consistency among all new DIS version 7 PDUs. For this experiment, the PDU status field was designated as 8 bits of padding, since this field will not be used in this experiment. Second, the DE fire PDU aim point record was not properly byte aligned as required.[5] An additional 32 bits were added, thus meeting the DIS standard for byte alignment. Third, the description and enumerations for the pulse shape field were not provided in PCR 152.[2] The DE Tiger team lead was notified, and an enumeration of zero was suggested and defined as 'other' to be used for this experiment. All of these changes were incorporated into PCRs 183 and 184.[4] Additional pulse shape models can be added along with the associated enumeration when required.

3.4. Network Design

The DMOC DE experiment simulations were connected on a separate virtual Local Area Network (LAN). The DMOC DIS filter[7] was placed between the DE experimental LAN and the ACE LAN. The DIS filter software was not modified, thus it did not pass any DE PDUs. During some of the tests, fire and detonate PDUs were allowed to pass onto the ACE network for fidelity/interoperability testing between the high-fidelity DE PDUs and legacy fire and detonate PDUs.

3.5. Scenario Design

The DE PDU experiment scenario was created in STAGE and JCATS, centered on N 37° 26′ 02.21″, E 127° 58′ 08.58. The upper right corner was at N 37° 46′ 09″, E 127° 23′ 09″. The lower left corner was at N 37° 06′ 18″, E 127° 32′ 56″. The DIS filter was configured to filter almost all ACE incoming PDUs, but to transmit all of the DE PDU experiment's entity state, fire, and detonate PDUs to the ACE LAN.

3.6. Unit Test

Once software development was complete, a series of unit tests were conducted to verify proper PDU structures and exchanges. During software unit testing, one issue was identified. The damage status PDU did not have an event ID field, which was included in the DE fire PDU. During the unit test, it was difficult to match the damage status PDU to the entity state and DE fire PDUs. The firing entity ID field in the damage status PDU was changed to the event ID field.

3.7. Integration Test

The integration test goals were to verify the DE PDUs were isolated from the ACE network and test basic DE PDU exchange algorithms. First, the F-16 HEL Fighter fired on fixed and moving targets generated by STAGE. The F-16 HEL sent DE fire, fire and detonate PDUs when engaging STAGE targets. STAGE generated damage status PDUs and entity state PDUs with the appropriate appearance bits set. The DISNAT data logger recorded all PDUs for data analysis, verifying correct DE PDU structures and PDU exchange sequences. During this PDU exchange, data recorded on the DISNAT PDU logger on the ACE network verified that no DE PDUs passed through the DIS filter.

3.8. Directed-energy Experiment Results

The experiments were categorized into three different tests: Test 1: HEL fighter engaging a fixed ground target, in this case, a stationary tank; Test 2: HEL fighter engaging ground and air moving targets, in this case, a moving tank and an F-15C fighter; and Test 3: a high-fidelity DE weapon engaging a low-fidelity target. The DIS experiment initial conditions are as follows:

1. Exercise ID: 2
2. User Datagram Protocol (UDP) Port: 2000
3. DIS Entity State Update rate:
   a. Air: 5 s Straight and Level
   b. Ground: 55 s
4. Dead Reckoning Algorithm:
   a. STAGE: 5
   b. F-16 HEL: 5

For each test, the JCATS simulation was also run to observe how non-DE modified simulations responded to DE specific PDUs. Test 1 experiment parameters are as follows:

1. F-16 HEL Fighter Weapon configuration
   a. Site ID: 48.16.1
   b. Aperture Diameter: 0.3 m
   c. Wavelength: 1.03E-06 m
   d. Peak Irradiance: 2000 W/m^2
   e. Pulse Rep. Frequency: 97,100 Hz
   f. Pulse Width: 10 s
   g. Status Flag: 0
   h. Pulse Shape: Other
   i. DE Aim point record type: DE Precision
2. Target: Non Moving Tank.
   a. Site ID: 48.8.27

The stationary tank broadcast entity state PDUs every 55 s. The F-16 HEL proceeded with an air-to-ground engagement, acquired the target, and fired the HEL once the target was acquired. Both DE fire and fire PDUs were transmitted. The DE fire PDU status flag was set to 3, representing the weapon on and state change. The fire PDU showed the correct event ID, target ID, world coordinate location, warhead type and the quantity was set to 1. After 1 s, another DE fire PDU was transmitted, and then STAGE transmitted a damage status PDU representing minor damage, fire present and white smoke. After 2 s, another DE fire PDU was transmitted showing the cumulative duration of 2 s with the status flag set to 3 representing the weapon on and state change. After 3 s, another DE fire PDU was transmitted incrementing the duration correctly. STAGE then transmitted an entity state PDU with the appearance bits set to slight damage and still active. After 3 s, the F-16 HEL transmitted a DE fire with the status flag set to 2 representing the weapon off and state change. The F-16 HEL also transmitted a detonate PDU with the correct event ID, weapon type, and detonation result. STAGE then transmitted a damage status PDU showing medium damage, moderate smoke, and gray smoke. Five seconds later, STAGE transmitted an entity state PDU with the appearance bits set for moderate damage and smoke plume, but still active. The DE engagement is summarized in Table 1.
Test 2 experiment parameters are as follows:

3. F-16 HEL Fighter Weapon configuration
   a. Site ID: 48.16.1
   b. Aperture Diameter: 0.3 m
   c. Wavelength: 1.03E-06 m
   d. Peak Irradiance: 2000 W/m^2
   e. Pulse Rep. Frequency: 97,100 Hz
   f. Pulse Width: 10 s
   g. Status Flag: 0
   h. Pulse Shape: Other
   i. DE Aim point record type: DE Precision

Table 1. F-16 – STAGE PDU engagement

Entity	PDU Type	Time	Parameters
F-16 HEL	DE Fire	1.32.075480	Duration: 0 Sec
F-16 HEL	Fire	1.32.075485	Kinetic Fuse Contact
F-16 HEL	DE Fire	1.33.075603	Duration: 1 Sec
STAGE Tank	Damage Status	1.33.112707	Avg Temp: 300; Minor Damage, White Smoke
F-16 HEL	DE Fire	1.34.075105	Duration: 2 Sec
STAGE Tank	Entity State	1.34.135941	Slight Damage
F-16 HEL	DE Fire	1.34.075105	Duration: 2 Sec, HEL Off
F-16 HEL	Detonation PDU	1.35.074731	Entity Impact
STAGE Tank	Damage Status	1.35.093095	Avg Temp: 300; Medium Damage, Gray Smoke
STAGE Tank	Entity State	1.39.250747	Avg Temp: 300; Medium Damage, Gray Smoke

Table 2. F-16–MiG 29 PDU engagement

Entity	PDU Type	Time	Parameters
F-16 HEL	DE Fire	19.42.011999	Duration: 0 Sec
F-16 HEL	Fire	19.42.011999	High Explosive, Fuse: Contact
F-16 HEL	DE Fire	19.42.061999	Duration: 0.5 Sec
MiG 29	Entity State	19.43.011999	Slight Damage
F-16 HEL	DE Fire	19.45.061999	Duration: 3.5 Sec
MiG 29	Damage Status	19.46.011999	Avg Temp: 300; Medium Damage, Gray Smoke
F-16 HEL	DE Fire	19.48.061999	Duration: 6.5 Sec
MiG 29	Damage Status	19.49.011999	Major Damage, Heavy Smoke, Black Smoke
F-16 HEL	DE Fire	19.49.061999	Duration: 6.5 Sec, HEL Off
F-16 HEL	Detonation PDU	19.49.161999	Entity Impact
MiG 29	Entity State	19.55.011999	Destroyed

4. Target: Moving Tank.
   a. Site ID: 48.8.27

The moving tank broadcast entity state PDUs every 5 s for straight level movement, and faster when the tank position exceeded the DIS dead reckoning parameters. These parameters are set such that if the tank position changes by more than a certain distance, an entity state PDU is transmitted with the new position. The F-16 HEL proceeded with an air-to-ground engagement, acquired the target, and fired the HEL once the target was acquired. The rest of Test 2 results were almost identical to Test 1, resulting in successful DIS PDU exchanges and target kill. The laser duration and damage were also identical.
Test 3 experiment parameters are as follows:

5. F-16 HEL Fighter Weapon configuration
   a. Site ID: 48.16.1
   b. Aperture Diameter: 0.3 m
   c. Wavelength: 1.03E-06 m
   d. Peak Irradiance: 2000 W/m^2
   e. Pulse Rep. Frequency: 97,100 Hz
   f. Pulse Width: 10 s
   g. Status Flag: 0
   h. Pulse Shape: Other
   i. DE Aim point record type: DE Precision
6. Target: MiG 29 Fighter, no DE capability.
   a. Site ID: 48.16.2

The F-16 proceeded with an air-to-air engagement, acquiring a threat aircraft as the moving air target, and fired the HEL once the target was acquired. Both DE fire and fire PDUs were transmitted. The DE fire PDU status flag was set to 3, for weapon on and state change. The fire PDU showed the correct event ID, target ID, world coordinate location, warhead type and the quantity was set to 1. After 0.5 s, DE fire PDUs were transmitted, as required by the draft standard. Status flags changed as expected, and the cumulative shot times were incrementing at 0.5 s. After 1 s, STAGE transmitted a damage status PDU; showing minor damage, fire present and white smoke. After 2 s, STAGE then transmitted an entity state PDU with the appearance bits set to moderate damage and smoke plume. After 3 s, STAGE transmitted a damage status PDU showing major damage, heavy smoke, and black smoke. One second later, STAGE transmitted an entity state PDU with the appearance bits set for destroyed and heavy smoke, and black smoke. The F-16 HEL STAGE PDU exchanges are shown in Table 2. Not all DIS PDUs are shown.

4. Conclusions

The DE PDU experiment was a unique opportunity to test proposed DE weapons models and their effects, correct discovered flaws in the model, and verify these corrections before incorporation into a formal standard. The errors would not have been discovered unless these experiments were conducted. Additional experiments have been conducted during the DE PDU event in August 2008, which included area and precision DE weapons, and incorporated real-world parameters and compared them to real-world data. The initial results show that these models are accurate for directed energy in a distributed simulation environment. Now, for the first time, many directed-energy simulations can be connected and can interact with each other in one

synthetic environment. Many research institutions can now connect their directed-energy simulations together for testing, experimentation, and research purposes.

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References

1. IEEE 1278.1. *Standard for Distributed Interactive Simulation – Application Protocols*. 1995.
2. DIS PDG Directed Energy Tiger Team. *Problem Change Request 152B Directed Energy Update*. June, 2006.
3. Szulinski J, Simpkins C. *Latency Testing In the USAF Distributed Mission Operations Environment*. September 2005.
4. DIS PDG Directed Energy Tiger Team. *Problem Change Requests 183, 184, 195 and 196; Directed Energy Updates*. May 2007, March 2008.
5. Sorroche J. *Directed Energy Experiment Test Plan and Results for the Advanced Concept Event 06.* March 2007.
6. Sorroche J, Szulinski J. *Bandwidth Reduction Techniques: An Update.* September 2005.
7. Sorroche J. *Directed Energy Experiment Test Plan and Results for the Advanced Concept Event 07.* March 2008.

Author Biography

Mr Sorroche is a senior systems engineer with Arctic Slope Regional Corporation Communications (ASRCC), and has 21 years professional experience; 14 years experience in the modeling and simulation field. He currently works at the DMOC and has been the engineering lead for the DMOC for many Virtual Flag, JEFX, and Blue Flag training events. He is the chair for the SISO TADIL TALES Product Support Group, the Link 11/11B Product Development Group and the DIS PDG DE Tiger team. Mr Sorroche is also the SISO liaison for the NATO Tactical Data Link Interoperability Testing Syndicate. Mr Sorroche is a co-recipient of the Fall 2002 SIWzie (Best Paper) Award for paper 02F-SIW-119 titled 'TADIL TALES', a co-recipient of the Spring 2006 SIWzie Award for paper 06S-SIW-074 titled 'A Mixed Architecture for Joint Testing', and a recipient of the Fall 2008 SIWzie Award for 08F-SIW-034 titled 'SIMPLE TALES'. He has Bachelors and Masters of Science Degrees in Electrical Engineering from New Mexico State University. He is a member of Tau Beta Pi and Eta Kappa Nu Honor Societies.

Appendix A. DE Fire PDU Structure, Final Draft

Field size (bits)	Directed-Energy Fire PDU fields	
96	PDU Header	Protocol Version—8-bit enumeration Exercise ID—8-bit unsigned integer PDU Type—8-bit enumeration Protocol Family—8-bit enumeration Timestamp—32-bit unsigned integer Length—16-bit unsigned integer PDU Status—8-bit record of enumerations Padding—8 bits unused
48	Firing Entity ID	Site Number—16-bit unsigned integer Application Number—16-bit unsigned integer Entity Number—16-bit unsigned integer
48	Event ID	Site Number—16-bit unsigned integer Application Number—16-bit unsigned integer Event Number—16-bit unsigned integer

(Continued)

Appendix A. (Continued)

Field size (bits)	Directed-Energy Fire PDU fields	
64	Munition Type	64-bit Entity Type record
64	Shot Start Time	64-bit Clock Time record
32	Cumulative Shot Time	32-bit floating point
96	Aperture/Emitter Location in Firing Entity Coordinates	*X*-component—32-bit floating point *Y*-component—32-bit floating point *Z*-component—32-bit floating point
32	Aperture Diameter	32-bit floating point
32	Wavelength	32-bit floating point
32	Peak Irradiance	32-bit floating point
32	Pulse Repetition Frequency	32-bit floating point
32	Pulse Width	32-bit floating point
16	Flags	16-bit Boolean field
8	Pulse Shape	8-bit enumeration
8	Padding	8 bits unused
32	Padding	32 bits unused
16	Padding	16 bits unused
16	Number of DE Records (*N*)	16-bit unsigned integer
varies	DE record # 1	Record Type—32-bit enumeration Record Length—16-bit unsigned integer $(6+K_1+P_1)$ Record-specific Fields—K_1 octets Padding to 64 bits—P_1 octets
	• • •	
varies	DE record # *N*	Record Type—32-bit enumeration Record Length—16-bit unsigned integer $(6+K_N+P_N)$ Record-specific Fields—K_N octets Padding to 64 bits—P_N octets

Total DE Fire PDU size = $704 + 8 \sum_{i=1}^{N} (6 + K_i + P_i)$ bits.

The Record Length $(6 + K_i + P_i)$ value shall be a multiple of 8 octets.

Appendix B. DE Fire PDU Flags

The meaning of the Boolean flags in this record are:

Name	Bit	Purpose
Weapon on/off state	0	Identifies the state of the DE weapon 0 – Weapon off 1 – Weapon on
State/update flag	1	Identifies a DE weapon state change 0 – Update due to heartbeat timer 1 – State change
Reserved	2-15	Reserved, set to zero

Appendix C. DE Record Type

The 32-bit enumerations for the DE record type field of DE records that are contained in the standard variable specification record section of the directed-energy fire PDU are shown below. DE records are assigned in the range of 4000–4499 until such time as additional numbers may be needed.

Field Value	DE Record Type
4000	DE precision aim point record
4001	DE area aim point record

Appendix D. Beam-spot Shape

The 8-bit enumeration for the beam-spot shape field in the DE precision aim point record is shown below.

Field Value	Beam-Spot Shape
0	Other
1	Gaussian
2	Top Hat

Appendix E. Area Aim point Record

Record Type	32-bit enumeration
Record Length	16-bit unsigned integer
Padding	16 bits unused
Beam-antenna Pattern Record Count	16-bit unsigned integer
DE Target Energy Deposition Record Count	16-bit unsigned integer
Beam-antenna Pattern record #1	288 bits (see 6.2.10.3)
•	
•	
•	
Beam-antenna Pattern record #*N*	288 bits (see 6.2.10.3)
DE Target Energy Deposition record #1	96 bits (see 6.2.22.4)
•	
•	
•	
DE Target Energy Deposition record #*M*	96 bits (see 6.2.22.4)
Padding to 64-bit boundary	*P* octets

Appendix F. Area Aim point Target Energy Deposition Record

Target Entity ID = 48 bits	Site Number—16-bit unsigned integer
	Application Site Number—16-bit unsigned integer
	Entity Site Number—16-bit unsigned integer
Padding	16-bits
Peak Irradiance	32-bit floating point

Appendix G. Beam-antenna Pattern Record

Beam Direction	Psi (ψ)—32-bit floating point
	Theta (θ)—32-bit floating point
	Phi (ϕ)—32-bit floating point
Azimuth Beamwidth	32-bit floating point

(Continued)

Appendix G. (Continued)

Elevation Beamwidth	32-bit floating point
Reference System	8-bit enumeration
Padding	24 bits unused
EZ	32-bit floating point
EX	32-bit floating point
Phase	32-bit floating point

Appendix H. Precision Aim Point Record

Record Type	32-bit enumeration
Record Length = 88	16-bit unsigned integer
Padding	16 bits unused
Target Spot World Location	*X*-component 64-bit floating point
	Y-component 64-bit floating point
	Z-component 64-bit floating point
Target Spot Entity Location	*X*-component 32-bit floating point
	Y-component 32-bit floating point
	Z-component 32-bit floating point
Target Spot Velocity	*X*-component 32-bit floating point
	Y-component 32-bit floating point
	Z-component 32-bit floating point
Target Spot Acceleration	*X*-component 32-bit floating point
	Y-component 32-bit floating point
	Z-component 32-bit floating point
Target Entity ID	Site Number—16-bit unsigned integer
	Application Number—16-bit unsigned integer
	Entity Number—16-bit unsigned integer
Target Component Identifier	8-bit enumeration
Beam-spot Shape	8-bit enumeration
Beam-spot Cross-section Semi-major Axis	32-bit floating point
Beam-spot Cross-section Semi-minor Axis	32-bit floating point
Beam-spot Cross-section Orientation Angle	32-bit floating point

Appendix I. PDU Type (Additions)

68	Directed-energy Fire PDU
69	Directed-energy Damage Status PDU

Appendix J. Entity Damage Status PDU Structure, Final Draft

Field size (bits)	Entity damage Status PDU fields	
96	PDU Header	Protocol Version—8-bit enumeration Exercise ID—8-bit unsigned integer PDU Type—8-bit enumeration Protocol Family—8-bit enumeration Timestamp—32-bit unsigned integer Length—16-bit unsigned integer PDU Status—8-bit enumeration Padding—8 bits unused
48	Damaged Entity ID	Site Number—16-bit unsigned integer Application Number—16-bit unsigned integer Entity Number—16-bit unsigned integer
16	Padding	16 bits unused
16	Padding	16 bits unused
16	Number of Damage Description Records	16-bit unsigned integer
varies	Damage Description Record # 1	Record Type—32-bit enumeration Record Length—16-bit unsigned integer $(6+K_1+P_1)$ Record-specific Fields—K_1 octets Padding to 64 bits—P_1 octets
	• • •	
varies	Damage Description Record # *N*	Record Type—32-bit enumeration Record Length—16-bit unsigned integer $(6+K_{N+}P_N)$ Record-Specific Fields—K_N octets Padding to 64 bits—P_N octets

Total Entity Damage Status PDU size = $192 + 8\,\Sigma\,(6 + K_i + P_i)$ bits.
The Record Length $(6 + K_i + P_i)$ value shall be a multiple of 8 octets.

Appendix K. Damager Description Record

Record Type	32-bit enumeration
Record Length	16-bit unsigned integer
Padding	16-bits unused
Damage Location	*X*-component 32-bit floating point *Y*-component 32-bit floating point *Z*-component 32-bit floating point
Damage Diameter	32-bit floating point
Temperature	32-bit floating point
Component Identification	8-bit enumeration
Component Damage Status	8-bit enumeration
Component Visual Damage Status	8-bit enumeration
Component Visual Smoke Color	8-bit enumeration
Fire Event ID	48-bit Event Identifier record (see 6.2.35)
Padding	16-bits unused

Appendix L. Component Identification

Field Value	Component
1	Entity Structure
2	Control System
3	Control Surface
4	Engine / Propulsion System
5	Crew Member
6	Fuse
7	Acquisition Sensor
8	Tracking Sensor
9	Fuel Tank / Solid Rocket Motor

Appendix M. Component Damage Status

Field Value	Damage Status
0	No Damage
1	Minor Damage
2	Medium Damage
3	Major Damage
4	Destroyed

Appendix N. Component Visual Damage Appearance

Name	Bits	Purpose
Fire	0	Describes presence of fire at the damage site 0 – No Fire 1 – Fire Present
Smoke	1-2	Describes presence of smoke emanating from the damage site 0 – No smoke 1 – Light Smoke 2 – Moderate Smoke 3 – Heavy Smoke
Surface Damage	3-4	Describes general surface appearance at the damage site 0 – Normal Appearance 1 – Light Charring 2 – Heavy Charring 3 – One or more holes burned complete through surface

Appendix O. Visual Smoke Color

Field Value	Visual Smoke Color
0	No Smoke
1	White Smoke
2	Grey Smoke
3	Black Smoke